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Transparent Flexible Capacitive Pressure Sensor Array

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Abstract—The realization of electronic skin (e-skin) that resemble human skin is increasingly in demand, particularly for wearable health monitoring, robotics, and human-machine interfaces. However, it is challenging to fabricate a large area array of pressure sensors due to the mutual crosstalk between sensors. In this study, we present a 4 × 4 transparent pressure sensor arrays developed using ITO-based electrodes and soft ecoflex as the dielectric. An interlayer of ZnO NWs was also introduced to improve the device’s performance. The sensor array exhibits an average capacitance of 9.4 pF and sensitivity of 0.16 kPa⁻¹ between 0 to 7 kPa. The results show the potential of using the presented sensor arrays for shape identification applications.

Keywords—Transparent electronics; flexible electronics; ZnO nanowires; pressure sensor; capacitive sensor.

I. INTRODUCTION

Human skin comprises of multiple types of receptors that are embedded at various depths in the skin to detect various contact parameters such as pressure, temperature, tensile stress etc [1, 2]. To match these capabilities, there is considerable interest in electronic skins (e-skin) for applications such as robotics, healthcare, wearables, human-and-machine interactions etc. [3, 4] To this end, a network of flexible and elastic pressure sensors is needed to convert mechanical inputs into electrical pulses. However, it is highly challenging to fabricate pressure sensors over a large area cost-effectively [5, 6].

Among various types of touch or pressure sensors (e.g. resistive [7], capacitive [8], piezoelectric [9], inductive [10] etc.) developed so far, the capacitive sensors have been widely adopted due to the ease of fabrication, simplicity of structure, simple readout electronics, and a low response to temperature and humidity variations [11]. The capacitive pressure sensors consist of a soft dielectric sandwiched between two conductive metallic layers [12]. To improve performance, different microstructures such as pyramids, domes, and pillars, nanofibers with porous structures, or filler materials with high dielectric constant have been introduced into the dielectric layer and at the interfaces. Our group has recently demonstrated that the introduction of ZnO nanowires (NWs) interlayer helps to improve the sensitivity by 50 times [13]. Many new applications could benefit if these pressure sensors are also optically transparent. For example, transparent sensors can be installed on glass without causing any visual hindrance [14]. At the same time, making a transparent pressure sensor array is an arduous task as each of the layers that make up the sensor must be transparent. Whilst graphene [15] and metallic NWs [16] based transparent pressure sensors and all transparent touch pressure arrays [5, 17, 18] have been reported, their lithography-assisted fabrication and vacuum-based deposition requirements are complex and expensive. In this study, we present a 4 × 4 array of transparent capacitive pressure sensors fabricated using simple and lithography-free patterning techniques. Transparent conducting metal oxide, Indium tin oxide (ITO), structurally transparent ZnO NWs, and transparent polymer Ecoflex were utilized as individual layers for the fabrication of the sensor array. The sensor array has huge potential for use in internet of sensing (IoS) applications and real-time shape detection of objects.

This paper is organised as follows: Section II discusses the materials used and the fabrication of the pressure sensors. The results related to the individual sensor and the array are discussed in Section III, and the key results and future aspects are summarised in Section IV.

II. MATERIALS AND METHODS

A. Sensor fabrication

Fig. 1a shows the schematic of the individual layers of the transparent sensor array. ITO-coated PET sheets with >80% transmittance and 100 Ω/sq. sheet resistance was purchased from Sigma Aldrich and was used as the electrodes for the sensor. Row and column electrode configurations were patterned over the ITO-coated PET sheet using a computer-controlled precision cutting machine with a plotter blade, Silhouette Cameo 2. The cutting machine helps with complex patterning without needing complex lithographic techniques or chemical etching procedures. The ITO-coated PET sheet was attached to a cutting mat for accurate positioning of the pattern cutting. The parameters such as the blade height, cutting speed, and cutting force were optimised to get sharp cuts for separating the ITO layer. Fig.1b shows the optical micrograph of the longitudinal cut pattern. ZnO NWs (purchased from Novorial) with average diameter and length of 10 nm and 10 µm, respectively, were dispersed in de-ionised water and sonicated to achieve uniform dispersion. The ZnO NW dispersion was spin-coated on the patterned ITO-coated PET sheet and annealed at 100 °C for 30 mins to remove the solvent. Ecoflex, with part A and part B mixed in a 1:1 weight ratio, was casted over ZnO/ITO electrodes and kept at room temperature for 20 mins for the partial curing. Finally, both the top and bottom electrodes with semi-cured Ecoflex were placed one over the other and cured at 50 °C.
under an external electric field, the non-dielectric capacitor was measured using a Keysight E4980AL precision LCR meter. When a force is applied, the capacitance was measured and calibrated using a load cell. The sensor performance was evaluated by applying force using a square blade cutter. The sensor performance was observed to be less sensitive in higher-pressure regions. The sensitivity of the sensor was also extracted from Fig. 2a, using the equation:

\[ S = \frac{(C - C_0)}{C_0} \delta P \]

Where \( C_0 \) is the initial capacitance without any pressure applied, \( C \) is the capacitance with pressure, and \( \delta P \) is the change in applied pressure. The sensor showed a sensitivity of 0.16 kPa\(^{-1}\). The concentration of ZnO NWs can be further optimized to improve the performance, which will be the focus of future work.

To further analyze the reliability of the sensor, a cyclic loading test was performed by loading and unloading from 0.5 to 5 kPa at a frequency of 0.5 Hz. The results (Fig. 2b) confirm that the sensor could clearly distinguish the various applied pressures and that it was also repeatable. To quantify further the sensor reliability, a cyclic repeatability test was also conducted for 500 cycles of 6.5 kPa, as shown in Fig. 3. The sensor performance was observed to be stable throughout the cycle, with similar capacitance variation observed at the initial (Fig. 3b) and final (Fig. 3c) stages. The sensor also responded and recovered quickly (within < 100 ms) throughout the cycle.

C. Sensor array application

A 4 × 4 array of pressure sensors that spreads over 5 × 5 cm\(^2\) was fabricated, as mentioned in section II. The initial capacitance distribution of the array is shown in Fig. 4a, which varies between 8 to 12 pF with an average capacitance of 9.4 pF. The result theoretically agrees with the capacitance of a parallel plate capacitor of 1 cm\(^2\) area and 250 μm thick Ecoflex with a dielectric constant of 2.8 at 1 kHz. To demonstrate the capacitive sensing capabilities of the sensor array, a 200 g (0.7 kPa) weight is kept on top of the sensor, and the variation in the capacitance distribution is recorded. Fig. 4b shows the photograph of the sensor with the weight kept on top, and the corresponding capacitance variation is plotted in Fig. 4d. To understand further, the sensor was placed on curved surfaces of different curvatures and the properties by the Maxwell-Wagner-Sillars polarization effect and hence improve the performance. Also, the light can pass through the gaps of the NWs, which makes the film structurally transparent.

B. Sensor performance

To evaluate the sensor performance, pressure ranging from 0 to 9 kPa was applied and the change in capacitance was measured, as shown in Fig. 2a. A linear variation in the capacitance was observed in the lower pressure regime. In contrast, it was observed to be less sensitive in higher-pressure regions. The sensitivity of the sensor was also extracted from Fig. 2a, using the equation:

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average capacitance variation was observed (Fig. 4e,f). At the lower bending radius, the strain experienced by the individual sensor is higher; and as a result, there is greater capacitance variations. Similarly, lower capacitive variation is observed for sensor place of surface with lower bending radius. These results confirm show the potential of presented sensors in applications such as robotics, smart widows, and as e-skins for shape and surface profile identification.

IV. CONCLUSION

In summary, we have demonstrated a transparent 4 x 4 pressure sensors array that can be used for sensing in the low-pressure regime of <10 kPa with 0.16 kPa⁻¹ sensitivity. The sensor was fabricated using a simple lithography-free patterning of the ITO on a flexible PET sheet, with soft Ecoflex as the dielectric layer. An interlayer of ZnO NWs was also introduced to improve the sensor performance in low-pressure regime. The sensor performance was observed to be reliable and repeatable with cyclic loading of pressure. The sensor array could be utilized for shape sensing in e-skin applications. The ZnO NW concentration needs to be further optimized to improve the device performance and transparency, which will be future work.

Fig. 3. a) Relative change in capacitance under cyclic loading and unloading at 6.5 kPa and 0.5 Hz. The magnified capacitance variation at b) initial and c) final stages.

Fig. 4. The sensor a) without and b) with a weight on top and the corresponding variation in the capacitance in c) and d), respectively. The sensor is wrapped around curved surfaces of e) 2.4 and f) 7 cm in radius.